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An Investigation to Reduce the Cutting Force in CNC Slot Milling Operation by Forecasting Optimum Process Parameters and Develop Precise Mathematical Model for It

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ABSTRACT

Industries frequently encounter several difficulties during milling operations, especially with cutting forces. Slot milling involves the machining of slots in materials using a milling cutter, and the challenges related to cutting forces can significantly impact the efficiency and quality of the milling process. CNC milling is widely used for machining of different types of materials in the manufacturing industry. Therefore, it is required to study process parameters and its behavior on materials which is not only to enhance the process but also make an effective and efficient path in metal cutting process. This research includes the effect of three input parameters i.e. feed rate, cutting speed and depth of cut on cutting force for Mild Steel. An empirical study gives the significant behavior of process or input parameter on machining properties. A mathematical study viz. ANOVA (Analysis of variance) gives the correlation in-between input or process parameters and machining or output properties for Mild Steel. It is also developed an equation for cutting force using a Regression model for the prediction of feed, speed and depth of cut. Values obtained from the mathematical models and Regression model was found to be very close to the data obtained from the experimental studies. The lowest cutting forces were obtained at high cutting speed and low feed rate and depth of cut.

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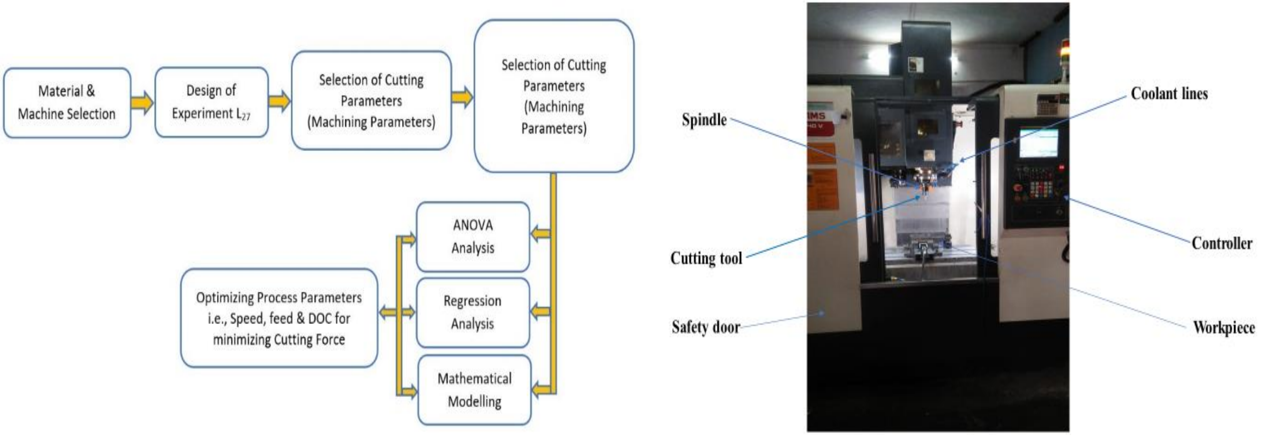
Graphical Abstract



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1. INTRODUCTION

Milling operations frequently cause problems for industries, such as tool wear, increased energy use, and shorter tool life. Excessive cutting forces can cause vibration and chatter during slot milling, leading to poor surface finish, dimensional inaccuracies. Controlling the cutting forces is essential to minimize vibrations and ensure smooth and accurate machining. The cutting forces can impose limitations on the material removal rate, restricting the efficiency and productivity of the slot milling process. Manufacturing sectors try to provide high-quality goods at a cheaper rate in order to retain competitive advantages in the market. A variety of metal cutting processes, such as turning, drilling, milling, boring, and others are used to make these items. Among these approaches, milling stands out as a commonly adopted metal cutting process used to manufacture planar surfaces with effectively material removal and high surface quality (1). Milling includes passing a workpiece through a revolving cylindrical tool fitted with several cutting blades (2). The main purpose of the art of metal cutting is to solve practical problems connected to the efficient and exact removal of metal from a workpiece. Achieving trustworthy and measurable forecasts of different technical performance metrics, preferably in the form of equations, is vital for creating optimization methods when determining cutting parameters during process design. By applying the technique of milling, machine components with specified dimensional precision and surface quality may be created on planar, obliquely, circular in shape and varied profile surfaces. The method is very profitable owing to the work of cutting instruments with several inserts. Surface quality is crucial for material for engineering, and surface roughness is a good measure of how well-surfaced a material is after it has been machined. It is impacted by elements including the workpiece's properties, the cutting environment, the material of the tool, and the shape (3). The significance of cutting forces in cutting processes cannot be overstated, as they directly influence several critical cutting performance factors. These factors include surface precision, tool wear, tool damage, cutting temperature, self-driven and forced vibrations, and others. The forces generated during metal cutting processes lead to deflections in the workpiece, tool, or machine structure, imparting energy to the machining system, which can lead to unstable vibrations or elevated temperatures. Hence, understanding and managing cutting forces are essential for optimizing the overall cutting process and achieving desired outcomes. In milling, excessive cutting pressures are undesirable because they lead to poor surface smoothness, dimensional errors, and more tool wear. The machinability of various materials is compared using measured cutting forces, which are also used for continuous control and monitoring of cutting operations, tool wear, and failures. Calculating cutting forces is useful for establishing fixture design, bearing loads, and machine power needs (4). In order to achieve good machinability indices, the machining force is crucial (5). To attain the highest level of machining process efficiency throughout the last ten years, the metal cutting operation has seen substantial increase. The main goal in achieving this efficiency is often to provide the optimal machining parameters, which calls for the creation and use of efficient process control via parameter optimization (6). The behavior of the forces of cutting and their connection to chip production and machining damages in orthogonal cutting of composites made from fibers have been thoroughly investigated in another research (7). Numerous variables, such as tool shape, cutting settings, temperature, and tool wear, have an impact on the cutting process. Tool geometry parameters are one of them that significantly affect the surface product's quality (8, 9). However, milling presents unique difficulties for process modeling when compared to other machining techniques. Accurately describing a cutting-edge geometry is one such problem. It is challenging to establish a general geometric model that accurately describes milling tools due to the large range of tool forms. As a consequence, creating milling model for each unique cutter shape has been the traditional technique in the literature. Additionally, cutting forces and the creation of chips are significantly influenced by the geometry of the cutting edge and the method employed to prepare it (10). Target precision in machining processes necessitates thorough analysis of the best circumstances, taking into account things like resource conservation, cutting conditions, and the impact on the environment (11-14). Minimizing cutting power in slot milling is an exciting goal in addition to guaranteeing surface quality. Analysis of surface quality and energy utilization in dry cutting milling of austenitic stainless steel has been the topic of certain investigations (15). In order to determine cutting power and force at the tool tip in slot milling processes analytically, Liu et al. devised a model (16). By using mathematical structures, mathematical models may be used to represent important features of reality. When compared to alternative ways of collecting the fundamental understanding about reality, they are more cost- and convenience-effective (17, 18). A "model" is a collection of equations that explain and connect all the variables and parameters that comprise a physical system or process. The process of "modeling" entails determining suitable equations that can be solved for a system of variables and parameters used in a process. These remedies, also known as simulations, imitate the actions of real systems and processes. Modeling is widely used in the physical sciences and engineering fields, sometimes referred to as "Applied Mathematics." Additionally, it has found use in fields like management science, finance, and economics that do not just focus on physical processes (19). In particular for slot milling on mild steel, this work proposes an effective mathematical model for calculating cutting forces and assessing cutting parameters in the milling process. The goal is to increase cutting force estimation's precision. After analyzing the literature, it is clear that this research makes a unique addition that may improve machining techniques since no other work of its like has been discovered. To avoid numerical integration, the model relies on curve fitting-based cutting force estimates. By using this model, the suggested ideal cutting circumstances are tested, and the optimal and nearly-optimal values of cutting parameters are identified based on optimum responses. The findings that have been provided might be useful for regional and global automotive businesses that work with related material families. The bulk machining and home metal cutting sectors both have comparable setups, making the study's conclusions valuable and helpful. In the context of this study, the development of an effective mathematical model for slot milling on mild steel opens up new possibilities for enhancing machining techniques and optimizing cutting processes. The proposed model's reliance on curve fitting-based cutting force estimates offers a more streamlined and accurate approach compared to traditional numerical integration methods. By using this model, researchers and engineers can gain deeper insights into the cutting forces involved in the milling process, leading to more informed decision-making and improved machining outcomes.

The use of appropriate cutting tools, optimizing cutting parameters, putting in place efficient cooling and lubrication systems, using the right workpiece fixturing, and utilizing advanced machining technologies, such as computer numerical control (CNC) and adaptive control systems, are just a few of the strategies and techniques that industries frequently use to address these challenges.

Moreover, the study's focus on slot milling on mild steel holds great significance for a wide range of industries, particularly those involved in automotive manufacturing, aerospace, and general machinery production. Mild steel is a commonly used material in these sectors due to its excellent mechanical properties, weldability, and affordability. Therefore, the findings of this research have the potential to impact numerous applications and contribute to advancements in various manufacturing processes. Furthermore, the optimization of cutting parameters based on the model's optimum responses can lead to substantial cost savings and resource conservation for companies. With the ability to identify optimal cutting conditions, manufacturers can reduce waste, minimize energy consumption, and extend the lifespan of cutting tools, ultimately increasing overall productivity and profitability. In addition to its practical implications, this study also advances the theoretical understanding of metal cutting processes, particularly in the context of milling. By considering tool geometry parameters and their impact on surface quality, researchers can devise improved cutting tool designs that enhance material removal rates and minimize surface roughness. As the manufacturing industry continues to evolve, the demand for sustainable and environmentally-friendly processes becomes increasingly critical. The proposed mathematical model, along with its focus on resource conservation and energy utilization, aligns with the broader goal of achieving greater sustainability in manufacturing operations. Manufacturers can use the model's results to optimize cutting conditions and minimize energy-intensive processes, contributing to an eco-friendlier approach to production. Overall, the unique contribution of this research lies in its combination of mathematical modeling, cutting force estimation, and optimization techniques in the context of slot milling on mild steel. By enhancing machining efficiency, surface quality, and resource utilization, this study can empower manufacturers to stay at the forefront of innovation and maintain a competitive edge in today's fast-paced global market. The proposed mathematical model for slot milling on mild steel presents a promising approach to address the challenges and complexities of metal cutting processes. Through accurate cutting force estimation and optimization of cutting parameters, this research offers valuable insights and practical solutions for enhancing manufacturing techniques. As industries strive for greater efficiency and sustainability, the findings of this study have the potential to drive positive change, benefiting both businesses and the environment. With continuous research and application, the pursuit of excellence in metal cutting and machining will undoubtedly lead to further advancements in the field of manufacturing.

2. EXPERIMENTAL SETUP & METHODOLOGY

The slot milling experiments were conducted using a state-of-the-art CNC vertical machining center (VMC-ACE Micromatic), equipped with a powerful spindle capable of delivering up to 30 kW of power and reaching a maximum speed of 8000 rpm. This machining center provided the necessary precision and stability required to carry out the slot milling process with optimal control over cutting parameters. Figure 1 shows the general idea map to calculate the milling cutting force model. Figure 2 and Figure 3 shows experimental setup and slot milling machining process.

For the milling process, Tungsten Carbide milling inserts were carefully selected due to their excellent wear resistance and high cutting performance. These inserts are known for their ability to withstand the demanding conditions of metal cutting, ensuring prolonged tool life and consistent machining results.

To quantify and analyze the cutting forces during the

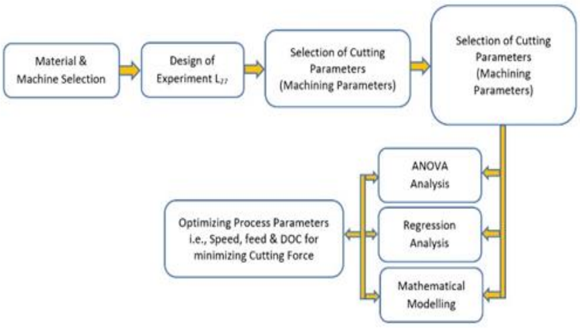

Figure 1. General idea map to calculate the milling cutting force model

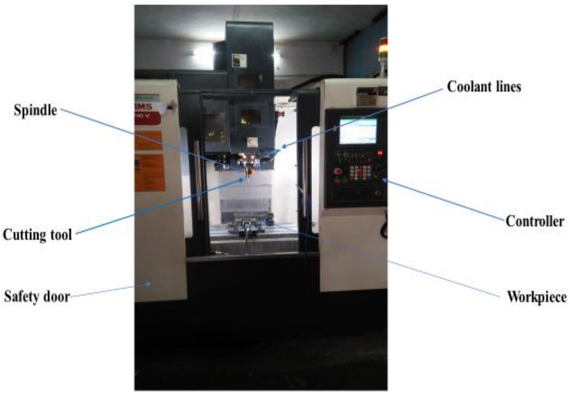

Figure 2. Experimental Setup for Slot milling operation

Figure 3. Machining Process

slot milling process, a mechanical dynamometer was employed. The dynamometer allowed for real-time measurement and recording of the cutting forces experienced during the milling operation. This data served as critical input for evaluating the machining performance and validating the mathematical model proposed in this study.

In order to efficiently design the experiments and analyze the collected data, the well-established Taguchi method was employed. Taguchi methodology is widely used in experimental design and optimization, offering robustness and efficiency in handling multiple variables simultaneously. The MINITAB Design of Experiment (DOE) software, a reliable and widely accepted tool for conducting statistical analyses, was utilized for implementing the Taguchi method.

A Taguchi L27 Orthogonal array, chosen based on its optimal arrangement of experimental runs, was employed for conducting the slot milling experiments. This design enabled the systematic variation of cutting parameters, such as cutting speed, feed rate, and depth of cut, within a controlled and efficient experimental framework. The use of orthogonal arrays minimizes experimental errors and reduces the number of required experimental runs, making the process time-effective and resource-efficient.

The data obtained from the Taguchi experiments were then used to develop a regression model. This model established a mathematical relationship between the cutting parameters (speed, feed, and depth of cut) and the cutting forces experienced during the slot milling process. By analyzing the regression model (20), researchers gained valuable insights into the impact of each parameter on cutting forces, enabling them to identify the optimal combination of cutting conditions for achieving desired machining outcomes.

The combination of advanced machining equipment, precise measurement techniques, and the systematic Taguchi experimental design showcases the meticulousness and rigor employed in this research. The comprehensive approach adopted in this study ensured that the results and findings are reliable, repeatable, and applicable in real-world manufacturing scenarios.

The utilization of Tungsten Carbide milling inserts, in conjunction with the CNC vertical machining center, demonstrated the practicality and industry relevance of the research. The proposed mathematical model, backed by experimental validation, promises to enhance the understanding and control of slot milling on mild steel, leading to improved machining efficiency and surface quality.

Overall, this chapter's experimental setup and methodology embody the pursuit of scientific excellence and the commitment to optimizing metal cutting processes. The combination of innovative technology, robust experimental design, and advanced statistical analysis sets a solid foundation for the subsequent analysis and discussion of results, which can contribute to advancements in manufacturing practices and benefit various industrial sectors.

Table 1 shows the different variable factors and their levels for experimentation work.

3. RESULT AND DISCUSSION

3. 1. ANOVA for Cutting Force

From the response diagram in Figure 4, It is observed that if speed is increased, cutting force getting increased. If feed is increased then cutting force also get increased. Similarly with increase in depth of cut, cutting force get increased. This analysis is carried out using an experimental data in Table 2.

In ANOVA analysis first of all S/N ratio is considered. The values of S/N ratios are given in Table 3.

TABLE 1. Variable Factors and their levels

Factors level	Speed (m/min) A	Feed (mm/min) B	Depth of cut (mm) C
1	10	6	1
2	13	9	1.5
3	16	12	2

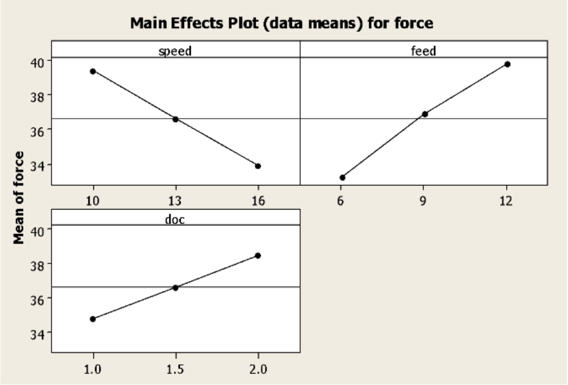

Figure 4. Response diagram for cutting forces

TABLE 2. Experimental data for depth and cutting force

Sr. No.	Doc (mm)	Feed (mm/min)	Speed (m/min)	Cutting Force (N)
1	1	6	10	33.18
2	1	6	13	32.71
3	1	6	16	40
4	1	9	10	37.17
5	1	9	13	34.99
6	1	9	16	33.19
7	1	12	10	40.28
8	1	12	13	36.75
9	1	12	16	34.02
10	1.5	6	10	35.75
11	1.5	6	13	33.18
12	1.5	6	16	31.25
13	1.5	9	10	39.66
14	1.5	9	13	36.11
15	1.5	9	16	34.39
16	1.5	12	10	42.55
17	1.5	12	13	39.27
18	1.5	12	16	37.21
19	2	6	10	35.96
20	2	6	13	33.71
21	2	6	16	32.08
22	2	9	10	42.04
23	2	9	13	40.15
24	2	9	16	34.45
25	2	12	10	48.08
26	2	12	13	42.63
27	2	12	16	37.56

TABLE 3. S/N ratios cutting force

Experiment No.	Cutting Force		S/ N Ratio
	Set 1	Set 2	
1	3.17	3.60	-10.61
2	3.62	3.67	-11.24
3	3.82	3.52	-11.30
4	3.52	4.06	-11.60
5	3.88	4.21	-12.15
6	4.34	4.24	-12.65
7	3.73	4.49	-12.31
8	4.4	4.28	-12.75
9	5.11	4.70	-13.82
10	3.3	3.29	-10.47
11	3.42	3.35	-10.59
12	3.64	3.24	-10.75
13	3.41	3.73	-11.06
14	3.64	3.73	-11.33
15	4.10	4.09	-12.25
16	3.59	3.91	-11.49
17	4.05	3.96	-12.05
18	4.62	4.08	-12.79
19	3.29	3.03	-10.01
20	3.23	3.15	-10.08
21	3.43	3.12	-10.31
22	3.32	3.45	-10.60
23	3.43	3.59	-10.91
24	3.70	3.53	-11.17
25	3.41	3.54	-10.81
26	3.85	3.75	-11.59
27	4.04	3.63	-11.68

3. 1. 1. CALCULATIONS FOR SIGNAL TO NOISE (S / N) RATIO

The S/N ratio, as described below, is utilized to evaluate the machining quality characteristic of force, which follows the principle of "smaller the better" (21).

$$\eta = -10 \log \left[\sum_{u=1}^{Ni} \frac{y_u^2}{Ni} \right] \tag{1}$$

Table 2 presents the data for the machining characteristic (force) and the corresponding S/N ratios, which were calculated using Equation 1 in the repeated trial condition. The trials were performed n times, and the responses for each trial, denoted as y1, y2, ..., yn, were used in the calculations. There are a total of 27 trials represented in the table, showcasing the resulting S/N ratios alongside the raw force data.

3. 1. 2. Response Table for Cutting Force

The sum of S/N ratios for different levels is done which is given in Table 4. Cutting force is being smaller the better characteristics. From the Table 4, it is observed that A1-B3-C3 is an optimum combination of parameters. It means Speed of 10 m/min; Feed of 12 mm / min & Depth of cut of 2mm is an optimum combination of parameters to obtain minimum cutting force.

Now,

$$M = (1/27) \sum_{i=1}^{3} A_i = \left(\frac{1}{27}\right) * (-3019.702) = -111.841 \tag{2}$$

3. 1. 3. Analysis of Variance (ANOVA) for Cutting Force

ANOVA is utilized to examine the processes that have a significant impact on the quality characteristics. The details are mentioned in Table 4. The calculations are performed using the following Equations3, where the readings for factor A at each level are utilized to demonstrate the calculations. The calculations for factors B and C are mentioned in Table 5.

Sum of square SS for factor A can be calculated by:

$$\text{Sum of square SS} = 3 * [(M_{A1} - M)^2 + (M_{A2} - M)^2 + (M_{A3} - M)^2] = 279.667 \tag{3}$$

Similarly SS for factors B and C can be calculated.

Then,

TABLE 4. Level Totals for S/N ratios

Factors	**A**	**B**	**C**
Levels	Speed	Feed	D.O.C.
1	-1068.99	-927.52	-981.66
2	-1004.56	-1023.51	-1007.29
3	-946.15	-1068.67	-1030.75
Total	-3019.70	-3019.70	-3019.70

$$\text{Mean Square MS} = \text{SS/ Degree of Freedom} = 279.667/2 = 139.883 \tag{4}$$

Similarly MS can be calculated for factors B and C.

Table 6 summarized the ANOVA analysis for cutting force.

Aforementioned table represents ANOVA for cutting force analysis; it is observed that “feed” is the most significant parameter affecting cutting force with 54% significance. The significant of speed and depth of cut is found to be 39% and 6%, respectively.

In the current case, the error variance or error mean square is determined by dividing the sum of squares (SS) with the lowest value by its degree of freedom.

$$\text{Error Variance } \sigma_e^2 = \frac{\text{Sum of Squares due to error}}{\text{Degree of freedom due to error}} = \frac{44.665}{2} = 22.33 \tag{5}$$

The F-Test (21, 22) is employed to identify the process parameters that have a substantial impact on the quality characteristics. The variance ratio denoted by F is given by $F = MS / \sigma_e^2$. A higher value of F indicates that the factor's effect is significantly greater compared to the error variance. When a particular factor contributes more to the total sum of squares, it has a greater ability to influence η. This influence is expressed as a percent contribution (%P), which is calculated as follows

$$\%P = SS / \text{Total sum of SS} \tag{6}$$

3. 1. 4. Contour Plot Analysis for Cutting Force

Graphs are useful tools for visualizing the response surface of a variable. However, when there are more than two independent variables, it becomes challenging or nearly impossible to represent the response surface graphically due to the limitations of three-dimensional visualization. For better understanding contour plots are developed using MINITAB 14.0 software.

TABLE 5. Average η by factor level

Factors	**A**	**B**	**C**
Levels	Speed	Feed	D.O.C.
1	-118.78	-103.06	-109.08
2	-111.62	-113.72	-111.92
3	-105.13	-118.74	-114.53

TABLE 6. ANOVA for cutting force analysis

Factors	**SS**	**DF**	**MS**	**F**	**%P**
Speed	279.67	2	139.83	6.26	39.43
Feed	384.89	2	192.44	8.62	54.27
D.O.C.	44.66	2	22.332	1	6.3
Total	709.22	6	354.61	-	100.00

As shown in Figure 5 for higher speed and lower feed, cutting force value is smaller and as feed is increase, cutting force would increase. As illustrated in Figure 6 for lower depth of cut and higher speed, force would be decrease, and as D.O.C. is increased, cutting force would increase as well.

As shown in Figure 7 for lower feed and depth of cut, cutting force is less. As feed and D.O.C. are increase; cutting force would also increase.

3. 1. 5. Co-Relation of Process Parameters

The co relations between the factors cutting speed, feed, depth of cut, cutting force are obtained by multiple linear regression analysis. The quality characteristic used for the force is ‘smaller the better’. The regression equations are obtained from MINITAB software 14.0. The regression equations are given in Equation 7 as below. The regression equation is

$$\text{Force} = 33.1 - 0.917S + 1.10\ f + 3.71\ d_c \qquad (7)$$

where, S= Speed, f = Feed, d_c = Depth of cut

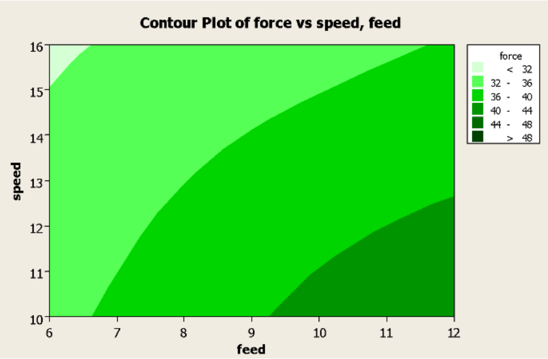

Figure 5. contour plot of cutting forces vs speed, feed

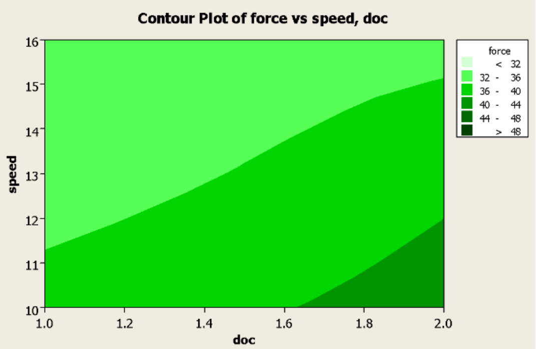

Figure 6. Contour plot of cutting forces vs speed, D.O.C

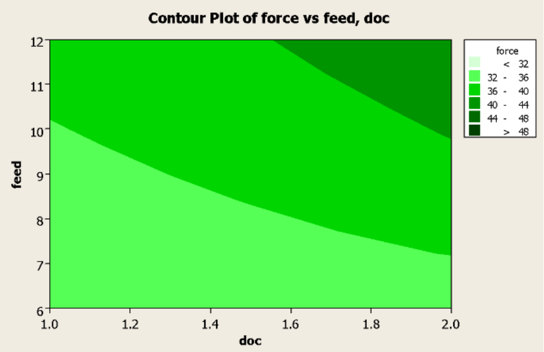

Figure 7. contour plot of cutting forces vs Feed, D.O.C

4. EMPIRICAL MODELING FOR CNC MILLING PROCESS PARAMETERS

4. 1. Modeling for Cutting Force

To develop an empirical model, the depth of cut is kept constant and its value will remain 1 for different values of feed and speed mentioned in Table 7. The quadratic graph as shown in Figure 8 of force vs speed for different values of feed, as shown in quadratic graph, if cutting speed is increase, cutting force would decrease. And from graph three quadratic equations are obtained.

As shown in Figure 8, three equations are obtained in the form of Force=aS^2+bS+c. Here a, b and c are constants and S represent speed. Values of the constants are separated from the equations and mentioned them in below Table 8 for future reference.

Now in the second step, from the constants vs feed graph, again three equations are obtained for depth of cut = 1mm.These equations are in the form of Force, speed and Feed [17]. For DOC=1mm, values of constants are mentioned in below Table 9. Tables 10 to13 summarized experimental data for different D.O.C. Table 4 stated the Values of constant related to feed.

TABLE 7. DOC= 1mm

Speed (m/min)	10	13	16	Feed (mm/min)
Force (N)	33.18	32.77	30.99	6
Force (N)	37.17	34.99	33.19	9
Force (N)	40.28	36.75	34.02	12

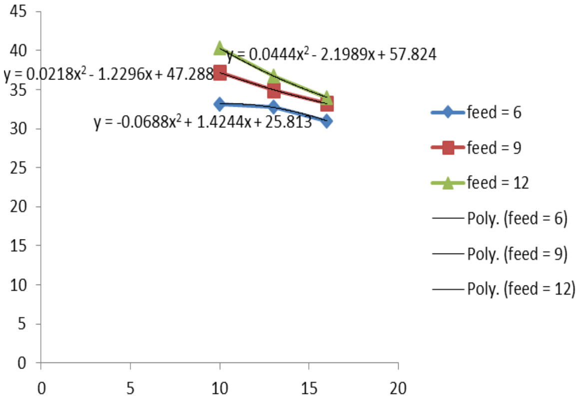

Figure 8. Plot of force Vs Speed at constant DOC = 1 mm

TABLE 8. Values of the constants related to feed

Feed	6	9	12
A	-0.068	0.021	0.044
B	1.424	-1.229	-2.198
C	25.81	47.28	57.82

TABLE 9. D.O.C. = 1mm

Constant	1	1.5	2
d	-0.003	-	-
e	0.084	-	-
g	-0.444	-	-
h	0.093	-	-
I	-2.287	-	-
j	11.78	-	-
k	-0.607	-	-
l	16.26	-	-
m	-49.92	-	-

TABLE 10. D.O.C. = 1.5 mm

Speed	10	13	16	Feed (mm/min)
Force	35.75	33.18	31.25	6
Force	39.66	36.11	34.39	9
Force	42.55	39.27	37.21	12

TABLE 11. D.O.C. = 1.5 mm

Feed	6	9	12
a	0.035	0.101	0.067
b	-1.674	-3.521	-2.652
c	48.93	64.71	62.29

TABLE 12. D.O.C. = 1, 1.5 mm

Constant	1	1.5	2
D	-0.003	-0.005	-
E	0.084	0.105	-
G	-0.444	-0.397	-
H	0.093	0.15	-
I	-2.287	-2.879	-
J	11.78	10.16	-
K	-0.607	-1.011	-
L	16.26	20.42	-
M	-49.92	-37.23	-

TABLE 13. D.O.C. = 2 mm

Speed	10	13	16	Feed (mm/min)
Force	35.96	33.71	32.08	6
Force	42.04	40.15	34.45	9
Force	48.08	42.63	37.56	12

Figures 9 shows the plot of constant Vs Speed at constant DOC = 1 mm. Figure 10 illustrates the plot of force Vs feed at constant DOC = 1.5 mm. The plot of constants Vs feed at constant DOC = 1.5 mm is shown in Figure 11.

Figure 12 shows the plot of force Vs Speed at constant DOC = 2 mm. The plot of constants Vs feed at constant DOC = 2 mm is shown in Figure 13. The plot of constants Vs DOC is shown in Figure 14. The below Table 15 shows the different values of constants for depth of cut 1, 1.5 and 2 mm.

The quadratic graph as shown in below of constants vs different values of depth of cut.

Finally, from above graph below equation is obtained in the form of speed, feed, depth of cut and force.

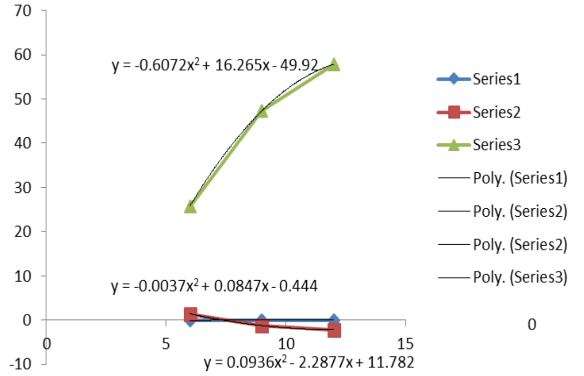

Figure 9. Plot of constant Vs Speed at constant DOC = 1 mm

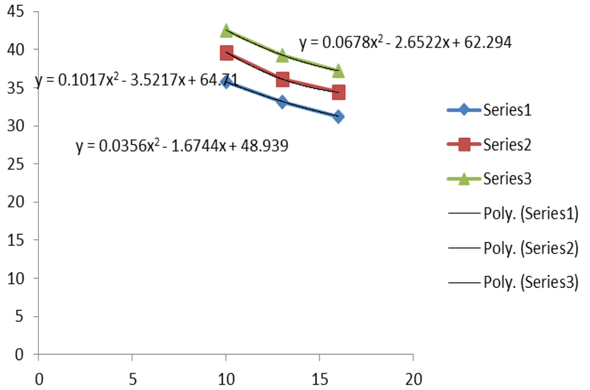

Figure 10. Plot of force Vs feed at constant DOC = 1.5 mm

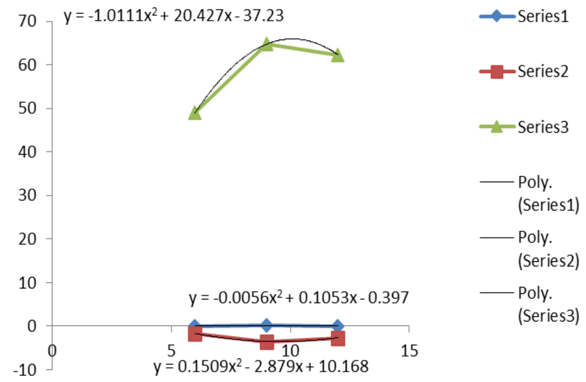

Figure 11. Plot of constants Vs feed at constant DOC = 1.5 mm

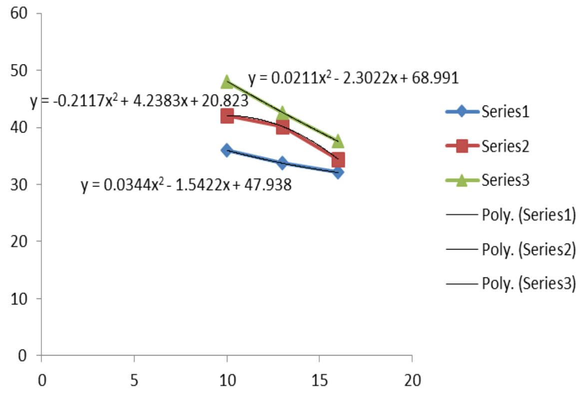

Figure 12. Plot of force Vs Speed at constant DOC = 2 mm

TABLE 14. Values of constant related to feed

Feed	6	9	12
A	0.034	-0.211	0.021
B	-1.542	4.238	-2.302
C	47.93	20.82	68.99

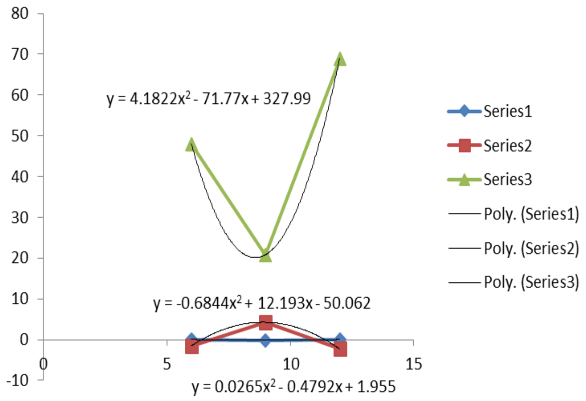

Figure 13. Plot of constants Vs feed at constant DOC = 2 mm

TABLE 15. D.O.C. =1, 1.5, 2 mm

Constant	1	1.5	2
D	-0.003	-0.005	0.026
E	0.084	0.105	-0.479
G	-0.444	-0.397	1.955
H	0.093	0.15	-0.684
I	-2.287	-2.879	12.19
J	11.78	10.16	-50.06
K	-0.607	-1.011	4.182
L	16.26	20.42	-71.77
M	-49.92	-37.23	327.9

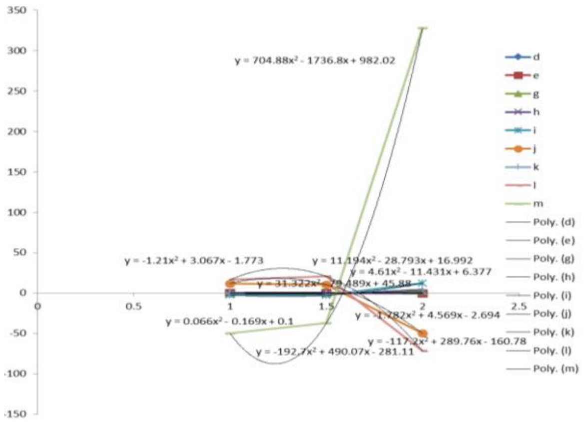

Figure 14. Plot of constants Vs DOC

$$\text{Cutting force} = [(0.066d_c^2 - 0.169d_c + 0.1) f^2 + (-1.21d_c^2 + 3.067d_c - 1.773) f + (4.61d_c^2 - 11.43d_c + 6.377)]S^2 + [(-1.782dc2 + 4.569d_c - 2.693) f^2 + (31.32d_c^2 - 79.48d_c + 45.88) f + (-117.2d_c^2 + 289.7d_c - 160.7)] S + [(11.19d_c^2 - 28.79d_c + 16.99)f^2 + (-192.7d_c^2 + 490d_c - 281.1)f + (704.8d_c^2 - 1736d_c + 982)] \quad (8)$$

where, S= Speed, f = Feed, d_c = Depth of cut

5. CONCLUSION

This study presents the results of an experimental investigation that examines how the feed rate, cutting speed, and depth of cut impact the cutting force in mild steel. It is found from the ANOVA (Analysis of variance), cutting force would be decreased with the increase of speed, and it would be increased with increase in feed and depth of cut. Thus, higher cutting speed is desired for minimizing cutting force requirement. By using an empirical & regression model, an equation has been developed for force to predict feed, speed and depth of cut. The validation equation has been checked by putting experimental data and similar values are obtained from all equations for Force. This approach can be utilized to quickly determine the optimal cutting parameters during machining, especially in situations where there is limited time for extensive experimental analysis.

6. REFERENCES

1. Qehaja N, Jakupi K, Bunjaku A, Bruçi M, Osmani H. Effect of machining parameters and machining time on surface roughness in dry turning process. Procedia Engineering. 2015;100:135-40. https://doi:10.1016/j.proeng.2015.01.351
2. Giridharan R, Kumar P, Vijayakumar P, Tamilselvan R. Experimental investigation and design optimization of end milling process parameters on monel 400 by Taguchi method. Int J Mech Eng Technol. 2017;8(2):113-22.
3. Özel T, Karpat Y. Predictive modeling of surface roughness and tool wear in hard turning using regression and neural networks. International journal of machine tools and manufacture. 2005;45(4-5):467-79. https://doi.org/10.1016/j.ijmachtools.2004.09.007
4. Kalidass S, Ravikumar TM. Cutting force prediction in end milling process of aisi 304 steel using solid carbide tools. International Journal of Engineering-Transactions A: Basics. 2015;28(7):1074-81. https://doi.org/10.5829/ije.2022.35.06c.08
5. Prasanth I, Ravishankar D, Manzoor Hussain M. Analysis of milling process parameters and their influence on glass fiber reinforced polymer composites (research note). International Journal of Engineering. 2017;30(7):1074-80. https://doi.org/10.5829/ije.2017.30.07a.17
6. Zainal Z, Rusli N, Shuaib N. Effect of Cutting Environment and Swept Angle Selection in Milling Operation. International Journal of Engineering. 2021;34(12):2578-84. https://doi.org/10.5829/ije.2021.34.12c.02
7. Sheikh-Ahmad J, El-Hofy M, Almaskari F, Kerrigan K, Takikawa Y. The evolution of cutting forces during slot milling of unidirectional carbon fiber reinforced polymer (UD-CFRP) composites. Procedia CIRP. 2019;85:127-32. https://doi.org/10.1016/j.procir.2019.09.043
8. Gao X, Cheng X, Ling S, Zheng G, Li Y, Liu H. Research on optimization of micro-milling process for curved thin wall structure. Precision Engineering. 2022;73:296-312. https://doi.org/10.1016/j.precisioneng.2021.09.015
9. Venkata Vishnu A, Sudhakar Babu S. Mathematical modeling & multi response optimization for improving machinability of alloy steel using RSM, GRA and Jaya algorithm. International Journal of Engineering. 2021;34(9):2157-66. https://doi.org/10.5829/ije.2021.34.09C.13
10. Denkena B, Biermann D. Cutting edge geometries. CIRP annals. 2014;63(2):631-53. https://doi.org/10.1016/j.cirp.2014.05.009
11. Lu Q, Zhou G, Zhao F, Ren Y, Li L, Luan X, et al. Topology optimization of oilstone components considering carbon emissions associated with honing processes. Journal of Cleaner Production. 2019;225:181-95. https://doi.org/10.1016/j.jclepro.2019.03.273
12. Camposeco-Negrete C, de Dios Calderón-Nájera J. Optimization of energy consumption and surface roughness in slot milling of AISI 6061 T6 using the response surface method. The International Journal of Advanced Manufacturing Technology. 2019;103:4063-9. https://doi.org/10.1007/s00170-019-03848-2
13. Zhou G, Lu Q, Xiao Z, Zhou C, Tian C. Cutting parameter optimization for machining operations considering carbon emissions. Journal of Cleaner Production. 2019;208:937-50. https://doi.org/10.1016/j.jclepro.2018.10.191
14. Sihag N, Sangwan KS. Development of a multi-criteria optimization model for minimizing carbon emissions and processing time during machining. Procedia Cirp. 2018;69:300-5. https://doi.org/10.1016/j.procir.2017.11.060
15. Muñoz-Escalona P, Shokrani A, Dhokia V, Imani-Asrai R, Newman ST, editors. A surface roughness and power consumption analysis when slot milling austenitic stainless steel in a dry cutting environment. Advances in Sustainable and Competitive Manufacturing Systems: 23rd International Conference on Flexible Automation & Intelligent Manufacturing; 2013: Springer.
16. Liu N, Zhang Y, Lu W. A hybrid approach to energy consumption modelling based on cutting power: a milling case. Journal of Cleaner Production. 2015;104:264-72. https://doi.org/10.1016/j.jclepro.2015.05.049
17. Davis D. Nomography and Empirical Equations. Reinhold. New York/Chapman & Hall, London; 1962.
18. Nguyen VN, Van Cao V. Experimental and Analytical Study on Postfire Reinforced Concrete Beams Retrofitted with CFRP in Flexure and Shear. Civil Engineering Journal. 2023;9(7):1610-29. http://dx.doi.org/10.28991/CEJ-2023-09-07-05
19. Gandhi A, Raval H. Analytical and empirical modeling of top roller position for three-roller cylindrical bending of plates and its experimental verification. Journal of materials processing technology. 2008;197(1-3):268-78. https://doi.org/10.1016/j.jmatprotec.2007.06.033
20. Mohammed AH, Mubarak HM, Hussein AK, Abulghafour TZ, Nassani DE. Punching Shear Characterization of Steel Fiber-Reinforced Concrete Flat Slabs. HighTech and Innovation Journal. 2022;3(4):483-90. http://dx.doi.org/10.28991/HIJ-2022-03-04-08
21. Gupta S. Fundamentals of Statistics: Sixth Revised & Enlarged Edition. Himalaya Publishing House, Delhi, Mumbia pp; 2011.
22. Gupta S. Statistical methods, sultan chand & sons. New Delhi. 2001;21.

Persian Abstract

چکیده

صنایع اغلب در طول عملیات آسیاب، به ویژه با نیروهای برش، با مشکلات متعددی مواجه می شوند. فرز اسلات شامل ماشینکاری شیارها در مواد با استفاده از فرز برش است و چالش های مربوط به نیروهای برش می تواند به طور قابل توجهی بر کارایی و کیفیت فرآیند آسیاب تأثیر بگذارد. فرز CNC به طور گسترده ای برای ماشینکاری انواع مختلف مواد در صنعت تولید استفاده می شود. بنابراین، بررسی پارامترهای فرآیند و رفتار آن بر روی مواد مورد نیاز است که علاوه بر بهبود فرآیند، مسیری موثر و کارآمد در فرآیند برش فلز ایجاد کند. این تحقیق شامل تأثیر سه پارامتر ورودی یعنی نرخ تغذیه، سرعت برش و عمق برش بر نیروی برش فولاد ملایم است. یک مطالعه تجربی رفتار قابل‌توجهی پارامتر فرآیند یا ورودی را بر روی خواص ماشینکاری نشان می‌دهد. یک مطالعه ریاضی یعنی. (ANOVAتحلیل واریانس) همبستگی بین پارامترهای ورودی یا فرآیند و خصوصیات ماشینکاری یا خروجی را برای فولاد ملایم نشان می دهد. همچنین معادله ای برای نیروی برش با استفاده از مدل رگرسیون برای پیش بینی تغذیه، سرعت و عمق برش ایجاد شده است. مقادیر به دست آمده از مدل های ریاضی و مدل رگرسیون بسیار نزدیک به داده های به دست آمده از مطالعات تجربی بود. کمترین نیروهای برشی در سرعت برش بالا و سرعت پایین تغذیه و عمق برش به دست آمد.